Frame Dragging in Optical Newton-Schrödinger System?

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Abstract: The general relativity effect of frame-dragging: the precession of test particles in the spacetime surrounding spinning masses, is demonstrated by solitons rotating the space around them via nonlocal nonlinearities, transferring angular momentum to probe beams.
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Recently, we have presented the optical emulation of gravitationally interacting quantum wavefunctions in the Newton-Schrödinger system, by means of a thermal nonlocal nonlinearity [1]. The Newton-Schrödinger system is a fundamental phenomenological model unifying quantum mechanics and Newtonian gravity. It describes the Newtonian gravitational potential that a quantum wavefunction induces on itself, affecting its Schrödinger-type dynamics. For these reasons, the Newton-Schrödinger system was extensively studied during the last few decades for achieving a better understanding of the interplay between quantum and gravitational effects, towards a quantum-gravity theory [2–4]. Specifically, in our study we utilized the mathematical equivalence between the Newton-Schrödinger system and the propagation of paraxial optical beams in nonlocal nonlinear media [1], and suggested that constructing specific initial wavefunctions can affect the interactions. In this context, the past few years has witnessed considerable interest in shaping the wavefunctions of optical and quantum wavepackets [5–7]. Thus far, however, the idea of emulating General Relativity (GR) phenomena has explored only the dynamics of quantum wavepackets (emulated by optical beams). Most certainly, it would be intriguing to shape wavefunctions specifically for controlling the actual nonlinear interaction between wavepackets.

Can we affect interactions between quantum particles in the Newton-Schrödinger framework by using wavefunctions with special structures? Can we transfer physical properties from one wavefunction to another using long-range interactions? The mathematical equivalence between the propagation of paraxial beams in nonlocal nonlinear media and the dynamics of quantum wavepackets in the Newton-Schrödinger framework brings this question to experiments: can we transfer angular momentum between optical beams in highly nonlocal nonlinear media? All these questions reflect on one of the most profound questions in quantum mechanics: nonlocality. Finally, ***can we emulate in our optical system actual GR phenomena that do NOT occur in Newtonian dynamic?***

Here we present theoretical and experimental results, demonstrating that angular momentum can indeed be transferred from one wavepacket to another, mediated by long-range interactions. We demonstrate rotating solitons that distort the space around them by altering the refractive index via a nonlocal nonlinearity, inducing precession for probed beams. This effect creates tidal acceleration specifically for extended beams in which different parts of the beam rotate at different rates. This effect is directly related to the frame dragging effect known from GR.

The evolution of optical wavepackets in our system is determined by coupling between the nonlinear paraxial equation and the Poisson equation that describes the refractive index change due to the thermal nonlinearity:

$$i\frac{\partial\psi}{\partial z}+\frac{1}{2k}\nabla_{\perp}^{2}\psi+\frac{k\Delta n}{n_0}\psi=0$$

$$\frac{\kappa}{\beta}\nabla^2\Delta n=-\gamma\left|\psi\right|^2,$$

where β describes the dependence of the change in the refractive index on the temperature change ($\Delta n=\beta\Delta T$), κ is the thermal conductivity, γ is the absorption coefficient of the material, and ψ is the slowly-varying amplitude of the electromagnetic field. The paraxial propagation of beams is analogous to Schrödinger dynamics of wavepackets, where the refractive index change plays the role of the gravitational potential. Hence, we expect to observe time-dependent gravitational effects by observing the evolution of the optical beam during propagation along the optical axis (z). The initial conditions of the system are two wavefunctions: One is a rotating dipole with angular momentum, and the others are weak beams ("probes") without any angular momentum. As observed in our simulations, angular momentum is indeed transferred between the wavepackets. The probe beams are starting to rotate and deform solely due to the interaction between the beams, affecting the trajectories and emulating tidal acceleration (Figure 1). It is important to emphasize that spiral/rotating soliton have been studied in the last two decades [8–10]. However, they were not used to rotate the space using long range interaction nor to induce precession on test particles. Here the emulation of tidal acceleration is observed specifically with extended beams, where different parts of the extended probe rotate at different rates, affecting the acceleration and trajectories.

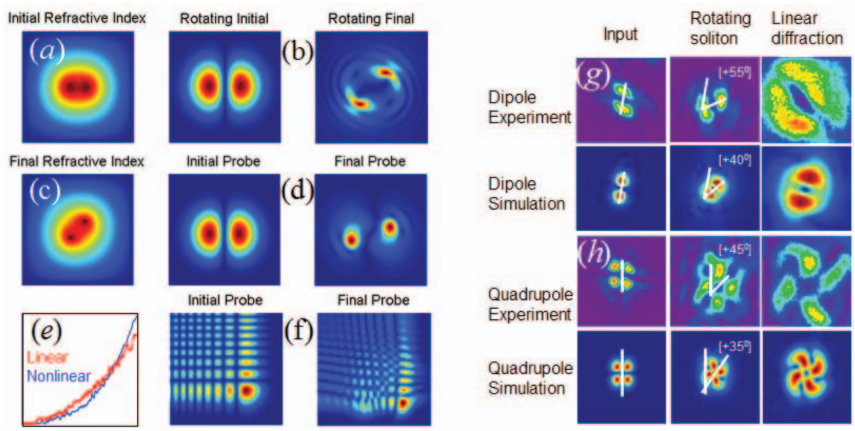

Figure 1: Long-range transfer of angular momentum between optical beams via the nonlocal nonlinearity (a-f) Numerical simulations of wavepackets interacting by a long range interaction. (a and c) the rotation of the nonlinear refractive index change. (b,d,f) Left: The initial wavefunctions: a wavefunction carrying orbital angular momentum creating rotation of the refractive index (b) and non-vortex wavefunctions acting as the "probes" (d and f). Right: final beams: the angular momentum is passed to the probe wavefunctions (d and f) creating tidal acceleration (f) and affecting the trajectory (e). (g-h) Preliminary experimental results with optical wavepackets: rotating beams are launched to propagate inside lead glass with a nonlocal nonlinear response: rotating dipole (g) and rotating quadrupole (h).

Interestingly, this effect can also be regarded as dragging of the frame of reference to a rotating frame, known from GR as "frame dragging". A rotating mass M with angular momentum J curves the space-time around it as denoted by the Kerr metric, describing the space-time in the environment around a rotating black hole [11] :

$$ds^2 = -dt^2 + \left(r^2 + a^2\right)\sin^2\theta d\varphi^2 + \frac{2Mr\left(dt - a\sin^2\theta d\varphi\right)^2}{r^2 + a^2\cos^2\theta} + \left(r^2 + a^2\cos^2\theta\right)\left(d\theta^2 + \frac{dr^2}{r^2 - 2Mr + a^2}\right),$$

where $c = G = 1$ and $a \equiv J/M$. This metric thus introduces, through the coupling between φ and t, a rotating reference frame, that will create precession of test particles. In our experiment, the initial wavefunction having large angular momentum can be thought of as effectively rotating the space around it, similar to what a rotating mass (e.g., a rotating black hole) would do to the space-time in the GR point of view. Initially, the test wavefunction ("probe") does not have angular momentum but it starts to rotate due the distortion of space, or – in our optical emulation – due to the distortion of the refractive index distribution. It is important to emphasize that this phenomenon should occur not only for the optical thermal nonlinearity, which acts like Newtonian gravity in the Newton-Schrödinger model, but rather it is present in any system where the interaction is long-range, such as dipole-dipole interaction between cold atoms [12], and every system with a transport mechanism.

Importantly, frame dragging does not occur in a strictly Newtonian system, rather it is a GR effect resulting from the dynamic change of the metric. Here we exploit the rotation of the intensity structure of the wavepacket to create a rotating refractive index distribution that manifests a similar effect of the rotation of space as frame dragging. In addition, we investigate these questions in the post-Newtonian regime, where the interaction is closer to Einstein's gravity, i.e. within the framework of gravitoelectromagnetic equations [13].

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